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Immobilization Thresholds of Electrofishing Relative to Fish Size

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Abstract.—Fish size and electrical waveforms have frequently been associated with variation in electrofishing effectiveness. Under controlled laboratory conditions, we measured the electrical power required by five electrical waveforms to immobilize eight fish species of diverse sizes and shapes. Fish size was indexed by total body length, surface area, volume, and weight; shape was indexed by the ratio of body length to body depth. Our objectives were to identify immobilization thresholds, elucidate the descriptors of fish size that were best associated with those immobilization thresholds, and determine whether the vulnerability of a species relative to other species remained constant across electrical treatments. The results confirmed that fish size is a key variable controlling the immobilization threshold and further suggested that the size descriptor best related to immobilization is fish volume. The peak power needed to immobilize fish decreased rapidly with increasing fish volume in small fish but decreased slowly for fish larger than 75–100 cm^3. Furthermore, when we controlled for size and shape, different waveforms did not favor particular species, possibly because of the overwhelming effect of body size. Many of the immobilization inconsistencies previously attributed to species might simply represent the effect of disparities in body size.

The immobilization thresholds of electrofishing have often been linked to fish size (Zalewski and Cowx 1990; Reynolds 1996). Most such studies have shown that large fish are easier to immobilize than small ones because they require less peak power (e.g., Reynolds and Simpson 1978; Zalewski 1985; Buettiker 1992; Anderson 1995). The effect of size is generally linked to body length (e.g., Taylor et al. 1957; Adams et al. 1972), but some authors have acknowledged the effect of total surface area (Emery 1984) and body form (Zalewski 1983). No adequate conceptual system exists to explain the effects of size on electroshock thresholds from the perspective of electric fields, but a few explanations have been offered. Most authors (e.g., Vibert 1967; Reynolds 1996) concur that the vulnerability of a particular fish species to electroshock increases with fish length because at a fixed voltage gradient, total body voltage increases with length (i.e., head-to-tail voltage is greater for large fish). Lamarque (1967) further explained that large fish have long nerves that require low voltage to stimulate (Rushton 1927). Nevertheless, Lamarque and Charlon (1973) showed that the voltage threshold for stimulation remains stable for fish nerves longer than 4 cm, suggesting that the effect of nerve length might be important for small fish but becomes trivial as fish size increases. Halsband (1967) considered size effects relative to pulsating currents and suggested that large fish are immobilized more efficiently because they have large muscles, the size of which prevents slackening between high-frequency pulses.

Disparities in immobilization thresholds over various electrical waveforms have been reported for some species. Halsband (1967) claimed that electricity pulsed at 90 Hz was most effective for immobilizing small cyprinids and that 80 Hz was most effective for salmonids, 50 Hz for the common carp *Cyprinus carpio*, and 20 Hz for the European eel *Anguilla anguilla*. Novotny and Priegel (1974) suggested that 15–40 Hz was effective for fishes such as walleye *Stizostedion vitreum*, yellow perch *Perca flavescens*, white bass *Morone chrysops*, and bluegill *Lepomis macrochirus*; 40–120 Hz was effective for fishes such as salmonids, largemouth bass *Micropterus salmoides*, and common carp; and 80–120 Hz was effective for the bullheads *Ameiurus* spp. In contrast, Corcoran (1979) reported that most ictalurids were best immobilized by 20 Hz, and Gilliland (1988) confirmed that 20 Hz was most effective for the flathead catfish *Pylodictis olivaris*. Emery (1984) stated that increasing pulse frequency favored the immobilization of small fish, implying that dif-

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ferential responses to frequency may lead to substantial gear bias. Miranda and Schramm (2000) reported significant differences in species assemblages measured with 15 and 60 Hz pulsed DC in the Mississippi River. The influence of pulse width has received less attention than pulse frequency, but the limited evidence available suggests that pulse width may have little effect on electroshock thresholds provided that it is larger than about 2 ms (Vibert 1967; Corcoran 1979; Kolz and Reynolds 1989).

Under controlled laboratory conditions, we measured the peak power needed by each of five electrical waveforms to immobilize eight fish species of diverse sizes and forms. These immobilization thresholds were then analyzed relative to species, body form, and several descriptors of fish size. The objectives of these analyses were to identify immobilization thresholds for the selected fish species according to electrical waveform, to elucidate what descriptors of fish size are most associated with those immobilization thresholds, and to determine whether the vulnerability of a species relative to other species remains constant as electrical waveforms change.

Methods

Test equipment.—All testing was conducted indoors in a polyethylene tank 2.0 m long, 0.5 m wide, and 1.0 m deep. The tank was filled to a depth of 10 cm with well water. The cross-sectional profile of the tank was equipped with two 1.6-cm-thick aluminum plate electrodes positioned perpendicular to the longitudinal axis of the tank. Electricity was supplied to the plates via a Smith-Root 15-D POW unit (Smith-Root, Vancouver, Washington) modified to allow continuous rather than discrete voltage control and equipped with additional smoothing capacitors to eliminate spikes and reduce ripples at the peak of the pulses (ripples averaged ±6% of the amplitude). Conditions within the tank produced a homogeneous electrical field with a constant voltage gradient. Homogeneity within the electrified field was verified through direct voltage gradient measurements made with a probe similar to that described by Kolz (1993). Specific conductivity (C_s [μS/cm]) and ambient water temperature (T_w) were recorded with a YSI 30/10 FT meter (Yellow Springs Instruments, Yellow Springs, Ohio). The meter read C_s at a specific temperature (T_s; in this case 25°C). Ambient water conductivity (C_w) was estimated from specific conductivity, specific temperature, and ambient water temperature (Reynolds 1996) as

$$C_w = \frac{C_s}{1.02^{T_s - T_w}} \qquad (1)$$

Electrical treatments and test fish.—Five electrical treatments were considered, including continuous direct current (DC) and pulsed DC with 110 or 15 Hz and 1-ms or 6-ms pulse widths (the last four are denoted PDC 110–1, etc.). For all treatments, the duty cycles (percent on-time during each cycle) were 100, 66, 11, 9, and 1.5, respectively. These pulse frequencies and widths were selected because they represented settings near the upper and lower range of the adjustments commonly allowed by commercially available units and encompassed a wide range of duty cycles. Peak voltage (V_{pk}), frequency, and pulse width were measured with a Tektronix THS720A oscilloscope (Tektronix, Beaverton, Oregon). Peak voltage measures the maximum amplitude attained by a pulse. Following Kolz and Reynolds (1989), V_{pk} was used to calculate peak power density (Pd) as

$$\mathrm{Pd} = C_w \cdot \left(\frac{V_{pk}}{h}\right)^2 \qquad (2)$$

where the distance between electrodes (h) was maintained at 65 cm except when treating the two smallest species with PDC 15–1; then, it became necessary to reduce h to 48 cm to increase Pd.

We applied the five electrical treatments to 12 species–size combinations selected because they included diverse body forms and were readily available from fish culture facilities or local streams (Table 1). Nevertheless, limited fish availability permitted application of all five treatments to only 8 of the 12 species–size combinations; thus, some species were not subjected to all waveforms. Prior to testing, fish were seined from culture ponds or streams, held in concrete raceways or polyethylene circular tanks for at least 2 weeks, and maintained in good health on a diet of live or prepared food depending on the species. During testing, randomly selected fish were transferred one at a time to the test tank and confined in the area between the two electrodes. After allowing the fish 3–10 s for to become oriented, we switched the current on when the fish were perpendicular to either electrode. Although each fish was tested only once, a treatment set was exposed to voltages incrementing from near zero to levels exceeding those needed to immobilize them within 3 s. The

TABLE 1.—Fish species–size combinations selected for study. Fish were obtained from aquaculture facilities, a local stream, and a private fish farm. Values represent means for fish of various size groups.

Species and size group	Length (cm)	Area (cm^2)	Volume (cm^3)	Weight (g)	Length–depth ratio	Source
Black crappie *Pomoxis nigromaculatus*	15.3	79.6	80.0	49.2	3.4	MSUAC[a]
Bluegill						
Small	6.8	17.4	12.5	5.0	3.4	MSFH[b]
Large	15.8	92.9	105.7	82.4	2.8	Private producer[c]
Bluntnose minnow *Pimephales notatus*	5.8	5.3	2.3	1.8	5.6	Catalpa Creek[d]
Channel catfish *Ictalurus punctatus*						
Small	6.2	7.4	4.5	1.8	7.2	MSUAC
Medium	16.3	29.9	30.8	30.0	7.0	MSUAC
Large	31.9	163.9	318.2	280.8	6.6	MSUAC
Creek chub *Semotilus atromaculatus*	6.2	7.4	4.1	2.6	5.8	Catalpa Creek
Hybrid striped bass[e]	17.6	73.4	98.4	71.0	4.5	MSUAC
Largemouth bass						
Small	7.4	11.8	5.5	4.6	7.4	TNFH[f]
Large	21.7	124.8	185.8	138.6	4.6	TNFH
Redfin darter *Etheostoma whipplei*	5.3	5.1	3.1	1.4	7.7	Catalpa Creek

[a] Mississippi State University Aquaculture Center.
[b] Meridian State Fish Hatchery, Mississippi Department of Wildlife, Fisheries and Parks.
[c] Calhoun County, Mississippi.
[d] Oktibbeha County, Mississippi.
[e] Female white bass × male striped bass *Morone saxatilis*.
[f] Tupelo National Fish Hatchery, U.S. Fish and Wildlife Service.

immobilization response was recorded as 0 if the fish was not immobilized and 1 if it was immobilized. As many as 18–35 fish were used per treatment, depending on the ease of identifying the immobilization threshold. The reactions of each fish were observed and recorded, but they were also videotaped via a camera positioned over the tank to allow verification of the accuracy of live observations.

Immobilization thresholds.—Field strength has traditionally been reported as voltage gradient, current density, or power density (voltage gradient × current density). More recently, Kolz (1989) suggested that immobilization thresholds depend in part on the fraction of the power density that is transferred to the fish. The power transfer model has been shown to reduce the variability of survey data (Burkhardt and Gutreuter 1995) and to adequately predict the power levels required to elicit capture-prone behavior in fish over a wide range of water conductivities (Kolz and Reynolds 1989; Miranda and Dolan, in press).

For each electrical treatment and species–size category, logistic regression was used to estimate the peak power density threshold required for a 0.95 probability of immobilization ($Pd_{0.95}$). The binary immobilization response for each fish (y) was regressed on the independent variable Pd in the model

$$\text{logit}(y) = \beta_0 + \beta_i \cdot F_i + \beta_1 \cdot \log_e(\text{Pd}), \qquad (3)$$

where β_0 is the intercept, $\beta_i \cdot F_i$ the differential effect attributed to the species–size category, and β_1 the slope parameter for $\log_e$(Pd). After regression, logit(y) was transformed to the probability $P(y)$ by rearranging equation (3) as

$$P(y) = \frac{\exp[\beta_0 + \beta_i F_i + \beta_1 \log_e(\text{Pd})]}{1 + \exp[\beta_0 + \beta_i F_i + \beta_1 \log_e(\text{Pd})]}. \qquad (4)$$

The predicted $Pd_{0.95}$ was then used to estimate the peak power transferred into the fish ($Pt_{0.95}$) by means of the equation

$$\text{Pt}_{0.95} = \text{Pd}_{0.95} \frac{\left(4\frac{C_f}{C_w}\right)}{\left(1 + \frac{C_f}{C_w}\right)^2} \qquad (5)$$

where C_f is the estimated "effective conductivity" (Kolz and Reynolds 1989) and the quotient is the inverse of the multiplier for constant power (Kolz 1989). We fixed C_f at 115 μS/cm as suggested by Miranda and Dolan (in press).

Effect of body size and form.—Three direct and one indirect measure of body size were considered. The direct measures included total length (tip of nose or mandible to tip of compressed caudal fin), total area (including all fins), and total volume (including all fins). Total length was measured for all fish after they were euthanatized the day following treatment. Area and volume were estimated from digital photographs of a subsample (N = 16–22/species) that was representative of the average size in each treatment using Image Tool software (University of Texas Health Science Center, San Antonio). Total wet weight was considered an indirect measure of body size because it manifests total body size but not its proportions. The size variables did not account for the effect that an elongated or compressed body form may have on immobilization thresholds. To construct an index of body form (H = total length/body depth), body depth was measured as the maximum vertical distance in the fish's body (excluding fins).

The relation between $Pt_{0.95}$ and the fish size variables was examined with the model

$$\log_e Pt_{0.95} = \beta_0 + \beta_1 \log_e S + \beta_2 H + \beta_j E_j \quad (6)$$

where β_0 represents the model's intercept, β_1 the slope parameter for size S (total length, total area, total volume, or total weight), β_2 the slope parameter for H, and β_j the slope parameter for the jth electrical treatment (E_j). Interactions among the three main effects also were included. Once the adequacy of each model was verified by residual analyses, the degree of association between $Pt_{0.95}$ and the S variables was indicated by the coefficient of determination (R^2).

Effect of species.—We tested whether the vulnerability of each study species relative to the others remained constant over electrical treatments. This analysis was limited to the eight species–size combinations for which all five treatments were applied (i.e., all sizes of black crappie, bluegill, channel catfish, and largemouth bass). The effect of species was tested with the model

$$\log_e Pt_{0.95} = \beta_o + \beta_i F_i + \beta_j E_j + \beta_1 \log_e S \quad (7)$$

where β_0 represents the model's intercept, β_i the slope parameter for the effect of the ith species, β_j the slope parameter for the effect of the jth electrical treatment, and β_1 the slope parameter for fish size. Equation (7) was fitted with the S descriptor identified by equation (6) as maximizing R^2. Interactions among the three main effects also were included. Of particular interest was the interaction between the class variables, F and E. A significant interaction between F and E would indicate that the vulnerability of a species relative to other species changed with electrical treatments, whereas a nonsignificant interaction would indicate that it remained relatively unchanged among electrical treatments.

Results

The 1,240 fish included in these tests encompassed a wide range of sizes encountered in freshwater. Mean total length ranged from 5 to 32 cm, area from 5 to 164 cm^2, volume from 2–318 cm^3, weight from 1 to 218 g, and the length–depth ratio from 2.8 to 7.7 (Table 1). Larger fish were not included because of physical limitations imposed by the experimental conditions. Species with smaller or larger length–depth ratios were not available.

Although we strove to keep ambient conditions constant to focus on the effect of fish size, some variability in water temperature had to be accepted owing to the seasonal availability of test fish. The water temperatures at which fish were held and tested ranged from 17°C to 27°C, averaging 22.4°C. Whereas specific conductivity was relatively invariable at 197 ± 5 μS/cm throughout the study, fluctuations in water temperature caused ambient water conductivity (equation 1) to range from 176 to 221 μS/cm. Peak voltages applied in these water conditions ranged from 12 to 1,100 V, and peak power densities ranged from 7 to 110,800 μW/cm^3.

Estimates of the amount of transferred power needed to immobilize 95% of the fish treated ranged from as high as 88,635 μW/cm^3 for darters exposed to PDC 15–1 to as low as 28 μW/cm^3 for large-bodied fish of several species treated with PDC at 110 Hz and DC (Figure 1). While the levels of $Pt_{0.95}$ (μW/cm^3) decreased as fish size increased, the total power transferred to fish (μW) increased with fish size. The decreases in $Pt_{0.95}$ relative to size were large for small fish but small for large fish. The effect of size on immobilization became minor when fish volume reached 75–100 cm^3, or roughly 15 cm in total length. The value of $Pt_{0.95}$ in equation (6) was highly influenced by all S variables considered; however, it was not affected (P = 0.93) by H or by the interactions among S, H, and E ($P \geq 0.31$), suggesting that any effect of body form was undetectable and that the effect of body size was similar across waveforms. When body form and the above interactions were removed from equation (6), length accounted for 91% of the variability in $Pt_{0.95}$, area and weight for 93%, and

TABLE 2.—Estimated coefficients of models relating the peak power transferred to fish during electrofishing and four measures of body size. Equations were estimated for five electrical treatments: DC, pulsed DC (PDC) with a frequency of 110 Hz and pulse widths of 6 and 1 ms, and PDC with a frequency of 15 Hz and pulse widths of 6 and 1 ms. See the discussion of equation (6) in the text for additional information on the models used. Asterisks indicate that coefficients are significantly different from zero ($P < 0.001$); within columns, values of B_j with different lowercase letters are significantly different ($P < 0.01$).

Model parameter	Body size measure			
	Length (cm)	Area (cm^2)	Volume (cm^3)	Weight (g)
β_0	10.001*	8.772*	7.884*	7.410*
β_1	−1.746*	−0.879*	−0.643*	−0.582*
β_j				
DC	0.000 z	0.000 z	0.000 z	0.000 z
PDC 110–6	−0.796 y	−0.835 y	−0.848 y	−0.822 y
PDC 110–1	−0.945 y	−0.980 y	−0.989 y	−0.940 y
PDC 15–6	0.789 y	0.722 y	0.718 y	0.774 y
PDC 15–1	3.611 y	3.548 y	3.559 y	3.592 y
R^2	0.909	0.927	0.951	0.924

volume for 95% (Table 2). The vulnerability of largemouth bass, bluegills, black crappies, and channel catfish in relation to each other remained relatively constant over electrical treatments, as seen in Figure 1 and indicated by the lack of significant ($P = 0.55$) interactions between the class variables F and E in equation (7).

Discussion

Immobilization thresholds were inversely related to the four body size variables. The range in R^2 values for models that included the size variables was only 4%. Such a narrow range is to be expected given that all the measures of body size considered are strongly correlated. Nevertheless, body volume had the strongest association with immobilization threshold. Under power transfer theory (Kolz 1989), body volume is intuitively a relevant variable because the power density applied to the water and the power transferred into the fish are both expressed in units of volume.

The lack of a relationship between the immobilization threshold and body form reinforces the notion that volume is the principal body size variable controlling immobilization by electrofishing. The body forms considered in this study comprised most of those commonly found in freshwater fish, ranging from laterally compressed forms such as those of *Lepomis* and *Pomoxis* spp. to elongated forms such as those of *Micropterus* and *Etheostoma* spp. Flatfishes are uncommon in the freshwaters of North America, but we did include adult *Ictalurus* spp. that have an elongated body with a depressed head. Missing from our study were the highly elongated fish such as *Esox* spp. (which have length–depth ratios near 7–8) and *Lepisosteus* spp. (which have ratios near 11–14 for adults and higher ones for juveniles). Given the lack of a relationship between the immobilization threshold and indices of body shape in the range 2.8–7.7, we hypothesize that inclusion of more elongated fish would not change our conclusions (or at most would lead to an unpromisingly weak relationship restricted to the extremes of the body shape spectrum).

The peak power densities needed to immobilize fish decreased rapidly with increasing size for fish smaller than 75–100 cm^3 (14–18 cm long) but decreased slowly for larger fish. Taylor et al. (1957) investigated the response of 3–34-cm rainbow trout *Oncorhynchus mykiss* to DC electrofishing in a homogeneous field and reported decreasing response thresholds as length increased to 25 cm but no clear threshold difference among longer fish. Similarly, Anderson (1995) found that the probability of capturing brown trout *Salmo trutta* increased until fish reached 20–25 cm but that after that point the probability increments were negligible. Zalewski (1985) collected multiple species and showed that the electrofishing capture probability in streams increased rapidly with fish size for small fish but that the increases became minor when fish reached about 50 g, which is consistent with the deceleration recorded in our trials. Our findings suggest that one electrofishing setting is unlikely to be equally effective over the entire length or age structure of a species with an extended size range. In some cases, the peak power levels (and possibly frequencies) required to immobilize small individuals may be so high that an effective electric field cannot be generated (e.g., due to water conductivity extremes, equipment

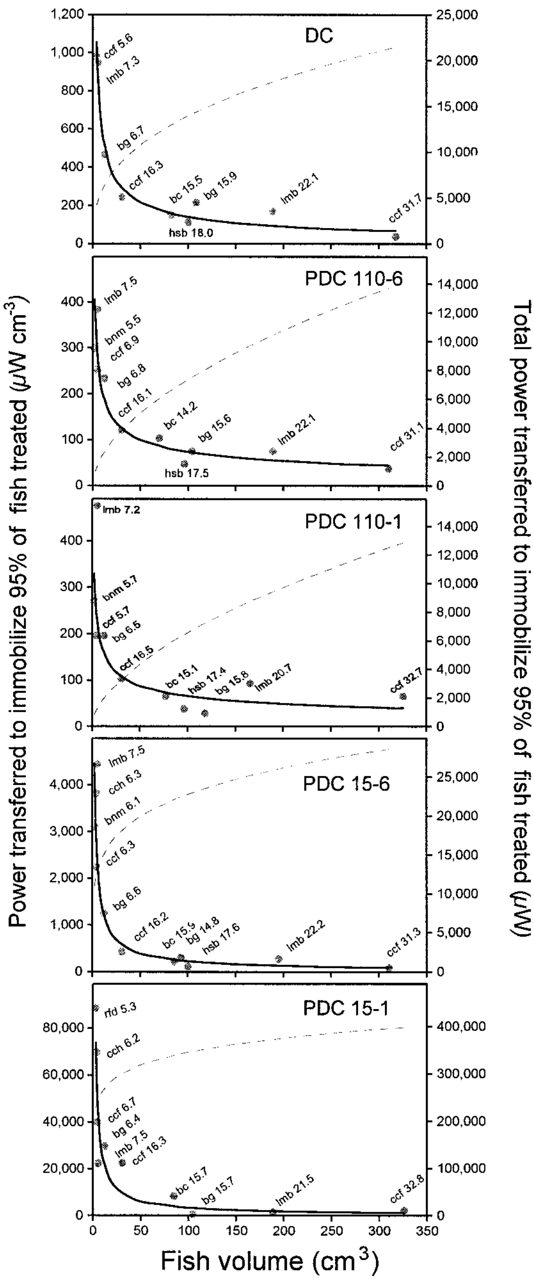

FIGURE 1.—The solid curves and circles show the relationships between the peak power density required to immobilize 95% of fish treated (lefthand *y*-axis) and fish volume (*x*-axis) for five electrical treatments. The dashed curves show the total power transferred to the fish (righthand *y*-axis), which is calculated as the product of the values on the lefthand *y*-axis and the *x*-axis. The acronym PDC stands for pulsed DC; in the accompanying numbers, the first is the frequency (Hz) and the second the pulse width (ms). The labels by each point indicate fish mean total length (cm) and species (bc = black crappie,

limits, or both). However, electrofishing should more often provide a less biased representation of the upper sizes of large-bodied species and possibly species with concise size distributions that exhibit small differences in size between juveniles and adults (e.g., *Etheostoma* spp.). Likewise, because of its size selectivity, electrofishing is unlikely to accurately portray the composition of fish assemblages with a mixture of small and large species unless sufficient power levels can be transferred to all of the size-classes present.

The vulnerability of species relative to each other remained constant over the five test electrical waveforms. Thus, the influence of fish size cannot be accounted for by the hypothesis that particular waveforms favor particular species. These results contradict the accounts of species selectivity summarized early in this article. There are several plausible explanations for this apparent discrepancy. Conceivably, our experiment did not include enough species or enough waveforms to detect species differences. We believe that this argument is unwarranted (1) because a wide range of duty cycles were included and (2) because the species varied greatly in size and biological characteristics and included catfish, which are reported to have atypical reactions to electricity (Corcoran 1979; Gilliland 1988). Alternatively, our homogeneous electric field may not have adequately recreated typical conditions. Unlike our homogeneous field, in a heterogeneous field fish are exposed to power density gradients that expand below and above the immobilization threshold, which could stimulate species differently and produce the differences reported by other authors.

It is also plausible that many of the differences previously attributed to species simply represent the effect of disparities in body size. The increased effectiveness in immobilizing small fish that is attributed to high pulse frequencies (Emery 1984) may just reflect the higher peak power afforded by high-frequency pulses. Such waveforms make possible higher instantaneous peak voltages that allow the threshold power needed to immobilize fish to radiate farther away from the electrodes, potentially producing larger electric fields. The size of the electric field created during electrofishing can differ over pulse frequencies if the power source

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bg = bluegill, bnm = bluntnose minnow, ccf = channel catfish, cch = creek chub, hsb = hybrid striped bass, lmb = largemouth bass, and rfd = redfin darter).

is operating near its limits and possibly cause differences in species catch rate, such as those noted by Miranda and Schramm (2000). Additionally, we found that low-frequency pulses with short width required high peak power levels to immobilize fish and thus tended to encourage forced swimming and thrashing rather than immobilization in all species tested. This observation is consistent with those made by Gilliland (1988), who reported that such pulses made the fish easier to detect but that collection often required a chase boat because the fish were not completely immobilized. Corcoran (1979) found that wider pulses caused fish to remain at the surface longer, which is consistent with the observation that such pulse settings transfer more power. Although some species differences are due to differences in the ability of fish to conduct electricity (Miranda and Dolan, in press), swimming power (Novotny and Priegel 1974), and other species peculiarities (e.g., Holliman 1998), the majority of the variability in the immobilization thresholds of the study species was accounted for by fish size.

This study confirmed that fish size is a key variable determining electroshock-induced immobilization and suggested that the size descriptor most related to peak power is fish volume. Further, whereas the relative amount of peak power ($\mu W/cm^3$) needed to immobilize fish decreased with increased fish volume, the absolute total power (μW) transferred into the fish increased, perhaps accounting for the easier immobilization of larger fish. Body form was not a factor. These differential immobilization thresholds demand careful study design and interpretation of survey data when electrofishing is used to make inferences about population and community structures. At power levels or frequencies below those needed to immobilize the smallest sizes, larger and older individuals and larger species may be overrepresented in the sample. Our study further suggests that different waveforms do not favor different species, possibly because of the overwhelming effect of body size. There is much that we do not understand about electrofishing, particularly the physiological responses to it. Without a better understanding of fish physiology relative to electrified fields, the results from experiments are difficult to interpret and hypotheses to accelerate the rate of knowledge acquisition are difficult to postulate. The science of electrofishing resides at the fringes of fish physiology, electrical science, and fishery science; rapid acquisition of knowledge requires successful collaboration among these disciplines.

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